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**Final Report**

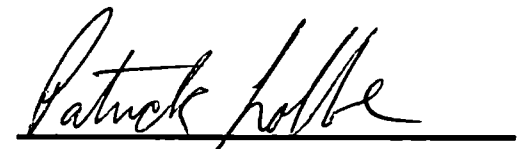
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**Mechanisms Test Bed Math Model  
Modification and Simulation Support**

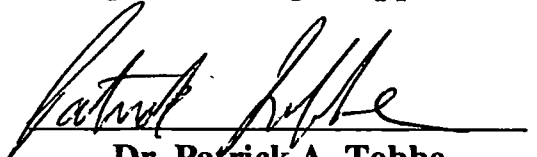
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## **1.0 INTRODUCTION**

This report summarizes the work performed under contract NAS8-38771. This work was initially awarded to Logicon Control Dynamics July 9, 1990. This contract primarily supports the Six Degree of Freedom Motion Facility (6DOF) and Flight Robotics Laboratory (FRL) at the George C. Marshall Space Flight Center (MSFC). The contract was modified and extended with several increments of funding to continue support for these and other activities. All work under this contract has been completed and documented [1-20]. Appendix A contains the report coversheets and introduction sections for this documentation.

Section 2.0 of this report summarizes the various activities performed by Control Dynamics under Tasks I through V. Summary remarks are presented in Section 3.0.

## **2.0 TASK SUMMARY**

This section of the report summarizes the activities performed under the five major tasks of the contract.

### **2.1 Task I**

Under this task, Control Dynamics developed a generic two body math model incorporating flexible body effects for the MSFC 6DOF facility. The equations of motion for the free flying vehicles were derived using a modified form of Lagrange's equations with quasi-coordinates. The assumed modes technique was used to integrate flexible body dynamics with rigid body motion. This technique allows elastic motion in all three axes for each body. Vehicle contact forces and control systems were also incorporated into the model.

The real time simulation was coded in FORTRAN and written in modular fashion. It was verified with comparison runs from TREETOPS and DADS. A pre-processing routine was also developed to compute simulation flexible body input files. All software was installed and tested on the Alliant FX-8 computer.

Control Dynamics also supported the transfer of existing math models from the VAX 11-750 computer to the Alliant FX-8 machine under this task.

## **2.2 Task II**

Under this task, Control Dynamics provided hardware and software support to the 6DOF Motion Facility and Flight Robotics Laboratory.

For the 6 DOF Motion Facility, Control Dynamics furnished support for the continuing development and run time modifications of the two body math model and motion system operations. Control Dynamics generated input data for the math model, maintained the interfaces between the hardware and software and analyzed the performance of the motion system. The Remote Manipulator System Simulation (RMSS) was upgraded to incorporate man-in-the-loop capability. The RMSS was modified to generate range/rate information for the Silicon-Graphics system and feedback for the operator.

Additional enhancements were made to the RMSS in support of the model validation process. Control Dynamics generated the algorithms and software required to compute loads at the strain gage locations on the flexible booms of the RMS. The free-free bending modes used to describe the elastic motion of these members were replaced with those based on the Craig-Bampton method. The mode superposition solution technique used by the RMSS was also replaced with a modified mode acceleration method developed by Control Dynamics. This method yielded a marked improvement in the performance of the simulation, especially in man-in-the-loop mode.

Control Dynamics also added the capabilities to the RMSS to accept orbiter thruster firing inputs and output manipulator point of resolution velocity data.

In support of the FRL, Control Dynamics installed a version of the RMSS on a Silicon Graphics system. This version of the RMSS has the same capabilities as that running at the 6-DOF Facility. However, the RMSS would not run in real time on the Silicon Graphics system. The inter process communication and data transfers were not fast enough on this parallel processing machine.

Control Dynamics also supported the development of the Solar Simulator in the FRL under Task II.

The solar simulator is a four degree of freedom machine used to simulate solar lighting conditions in the FRL. It consists of a carriage with six 6W spot lights capable of traversing the long axis of the flat floor. The carriage rotates and the intensity of the lights can be controlled. The fourth axis is a curtain in front of a light box used to simulate the earth's albedo. The curtain has since been removed.

The solar simulator can be used independently or in conjunction with the overhead crane. Provisions are made to synchronize the solar simulator movements with the Dynamic Overhead Target Simulator (DOTS) for simulation and safety purposes. The solar simulator is controlled by a personal computer. Control Dynamics developed the algorithms and software required to control the solar simulator. In the current scheme, the user specifies a location on the floor at which the lights should point (usually the fixed spacecraft mock-up) and an orbital period. The software assumes the orbit is circular, leading to a constant rotational speed for the lights. The commanded rotation of the carriage and the location of the fixed mock-up determines the required translation of the carriage. The distance between the lights and the fixed mock-up determines the required intensity (shutter opening) of the lights. The user enters the intensity verses distance

information in a look-up table. Another look-up table uses the angle of the simulator relative to the mock-up to determine the required opening of the curtain.

The software for the control of the solar simulator is written in Borland C under DOS. The software is of modular design with a cycle time of 0.5 seconds.

### **2.3 Task III**

Control Dynamics supported the development and operation of the Coupled Multi-body Spacecraft Controls Test Bed under Task III. This test bed is composed of a 4000 pound air bearing vehicle with an on board control computer, rate gyro, accelerometers, air thrusters, and control moment gyro. The vehicle is tied to ground through a planar three jointed flexible manipulator. Control Dynamics developed the mechanical and electrical requirements for the manipulator members, joints, and air bearings as well as an upgraded CMG. Control Dynamics worked with MSFC in the design, fabrication, and assembly of these components. The manipulator and air bearing vehicle control algorithms, hardware/software communication, and user interface were also developed by Control Dynamics.

A detailed finite element model and TREETOPS simulation of the test bed were constructed in support of modal tests, manipulator and vehicle control system evaluations, and end point control unit studies. Control Dynamics operated and maintained the test bed during these studies and contributed to numerous publications. A detailed study was also performed to evaluate an active isolation system for the RMS. This end effector device would minimize loads transmitted to the manipulator during Space Station assembly activities.

## 2.4 *Task IV*

Task IV is composed of a variety of support activities for the Automatic Rendezvous and Capture (ARC) program. Initially, for the DOTS of the FRL, Control Dynamics performed a series of tests on the hardware to characterize the performance of the analog rate servos and digital joint controllers. These tests were run with the DOTS under control of the micro-VAX computer system. A two body simulation was developed and interfaced to the DOTS in support of verification testing of an automatic rendezvous sensor system. This simulation was later modified for inputs from a force/torque sensor and used in contact dynamics studies.

Control Dynamics worked with MSFC to develop requirements for a new DOTS control and simulation host computer. Upon the procurement of the Night Hawk systems, Control Dynamics supported MSFC with the installation of new joint encoders and wiring. The remaining hardware for the DOTS was then interfaced to the Night Hawk and the CMR21 removed. The DOTS software and two body simulation were ported to the Night Hawks and modified for the new operating systems. The operation of the DOTS and the AR&C simulation were then verified through a series of system characterization tests.

The software was then modified to take advantage of the real time operating system on the Night Hawk to reduce the system cycle time. The joint controllers were redesigned and verified. The solar simulator was also interfaced to the DOTS and the Night Hawks. A set of solar simulator user commands were developed for script file or interactive mode of operation and interfaced with the DOTS software. The DOTS software was also modified to compute the appropriate simulator commands during hardware-in-the-loop tests. Control Dynamics also supported the hardware fabrication of a series simulated flight computer boards.

A Global Positioning System (GPS) simulation was written by Control Dynamics in support of the AR&C program. The GPS simulation developed under this task is a digital simulation of multiple GPS receivers. All functional elements of the GPS system are simulated including the GPS constellation and user receiver processing output. The GPS messages are functionally simulated so that all significant error sources, such as ephemeris errors, clock errors, selective availability error, GDOP error, etc., are included. The output from the simulation is configured to precisely emulate the output from a specifically prescribed GPS receiver unit. Additionally, the GPS simulation was hosted on the NASA Night Hawk computer where it is used to simulate multiple GPS receivers during Hardware-in-the-Loop testing of the Automated Rendezvous and Capture (AR&C) System.

Control Dynamic conducted analytical studies involving engine control systems with emphasis on electro pneumatic actuators. The focus of the study was the performance of the pneumatic actuator as compared to the hydraulic actuator in a TVC system.

Non-linear and linear simulations were created to aid in the investigation. Three possible control strategies for controlling a pneumatic actuator were presented. The three strategies were : position only feedback, position and pressure feedback, and position and piston rate feedback. Control implementation issues were not addressed.

The mass properties for an RL-10 engine were used as a plant model. Models of a pneumatic actuator were presented. Compressibility of the gas (hydrogen) and leakage across the piston were taken into account for the model of the pneumatic actuator. A simple servo valve model was employed.

From the results presented, the position and pressure feedback system showed the greatest promise in meeting performance criteria. Differences in the linear and non-linear simulations were noted. The disturbance rejection illustrated by the non-linear simulation showed poor performance when the servo valve saturates.



The position only controller requires a complex control system to meet the performance criteria. The position and pressure feedback system (with negative pressure feedback) results in a soft system. A position controller could be used to increase the bandwidth sufficiently to reject noise given the flow demand does not exceed the capacity of the supply system.

When employed with a positive pressure feedback system, a stiff system results. However, a fairly complex pressure controller would be required for stability. The position and piston rate feedback system illustrated good results with a simple controller.

## **2.5    *Task V***

Under Task V of this contract, Control Dynamics assisted MSFC in the development, fabrication, and testing of a Lightning Imaging System (LIS) and a Solar X-Ray Imager (SXI). This support consisted of the following activities: assembly and wiring of GSC/Breadboard card cages, cards, and equipment racks; building various coaxial, twin axial, ribbon and discrete conductor cables; functionally checking test equipment; incorporating engineering changes on flight boards; supporting integration of LIS and TRMM spacecraft.

### **3.0 SUMMARY**

A wide variety of activities were performed for the Marshall Space Flight Center Six Degree of Freedom Motion Facility and Flight Robotics Laboratory. These activities included the development and operation of the two flexible body and Remote Manipulator System Simulation, Dynamic Overhead Target Simulator software and control systems, Global Positioning System simulation, and Manipulator Coupled Spacecraft Controls Testbed. Technician support was also provided for the Lightning Imaging Sensor and Solar X-Ray Imaging programs. As a result of these activities, significant hardware in the loop simulation capability has been developed in the aforementioned facilities.

**REFERENCES**

1. Compton, J. "Mechanism Test Bed Flexible Body Model Report," July 1991.
2. Tobbe, P. and C. Naumann, "Automated Rendezvous and Capture," AIAA Space Programs and Technologies Conference, Huntsville, Alabama, March 1992.
3. Tobbe, P. and P. Williams, "RMS Software Overview and Operations Manual," February 1993.
4. Dendy, M., "Characterization Test Procedure and Results for the DOTS Joint Servo System," June 1993.
5. Montgomery, R., Tobbe, P., Weathers, J., Ghosh, D. and J. Garrison, "A Testbed for Research on Manipulator - Coupled Active Spacecraft," AIAA Guidance, Navigation, and Control Conference, Monterey, California, August 1993.
6. Dendy, M., Tobbe, P. and C. Naumann, "Results of the DOTS Joint Position Response Tests," August 1993.
7. Dendy, M. and P. Tobbe, "DOTS Encoder Alignment Procedure," September 1993.
8. Tobbe, P. and M. Williamson, "A Study of Active Isolation Systems for the RMS," July 1994.
9. Williamson, M., "Update to the Characterization Test Procedure for the DOTS Joint Servo System," July 1994.
10. Montgomery, R., Ghosh, D., Tobbe, P., Weathers, J., Manouchehri, D. and T. Lindsay, "Testing of an End-Point Control Unit Designed to Enable Precision Control of Manipulator-Coupled Spacecraft," AIAA Space Programs and Technologies Conference and Exhibit, Huntsville, Alabama, September 1994.
11. Tobbe, P. and T. Howsman, "RMS Math Model Upgrades and Simulation Validation Support," September 1994.
12. Williamson, M., "Feasibility Study of a Pneumatic Actuator for TVC Control," October 1994.
13. Montgomery, R., Tobbe, P., Weathers, J. and T. Lindsay, "Simulation and Testing of a Robotic Manipulator Testbed," Tenth VPI&SU Symposium on Structural Dynamics and Controls, Blacksburg, Virginia, May 1995.

14. Compton, J., "Simulation Output Summary - Statistical Model of a Global Positioning System Receiver and Constellation," May 1995.
15. Compton, J., "Simulation User's Manual Statistical Model of a Global Positioning System Receiver and Constellation," May 1995.
16. Naumann, C., "Solar Simulator Interface - Version 0.1," July 1995.
17. Williamson, M., "Results of the DOTS Joint Position Response Tests," October 1995.
18. Williamson, M. and C. Naumann, "Dynamic Overhead Target Simulator Users' Guide," October 1995.
19. Naumann, C., "DOTS Software Overview," October 1995.
20. Tobbe, P., Sutton, W., Bryan, T. and C. Naumann, "NASA MSFC Hardware in the Loop Simulations of Automatic Rendezvous and Capture Systems."
21. Lakshmanan, P., "RMS Parallelization at the Flight Robotics Laboratory on the Silicon Graphics Computer."

## **APPENDIX A**

## ***APPENDIX DESCRIPTION***

This appendix, as requested by MSFC, contains the cover sheets and introductory sections for the documentation written under contract NAS8-38771. The reports and viewgraph presentations are ordered chronologically as in the list of references.

**Mechanism Test Bed  
Flexible Body Model  
Report**

**Prepared for:**

**National Aeronautics and Space Administration  
George C. Marshall Space Flight Center  
Marshall Space Flight Center, AL 35812**

**Under Contract No.  
NAS8-38771**

**by**

**Jimmy Compton**

**July 1991**

**LOGICON**

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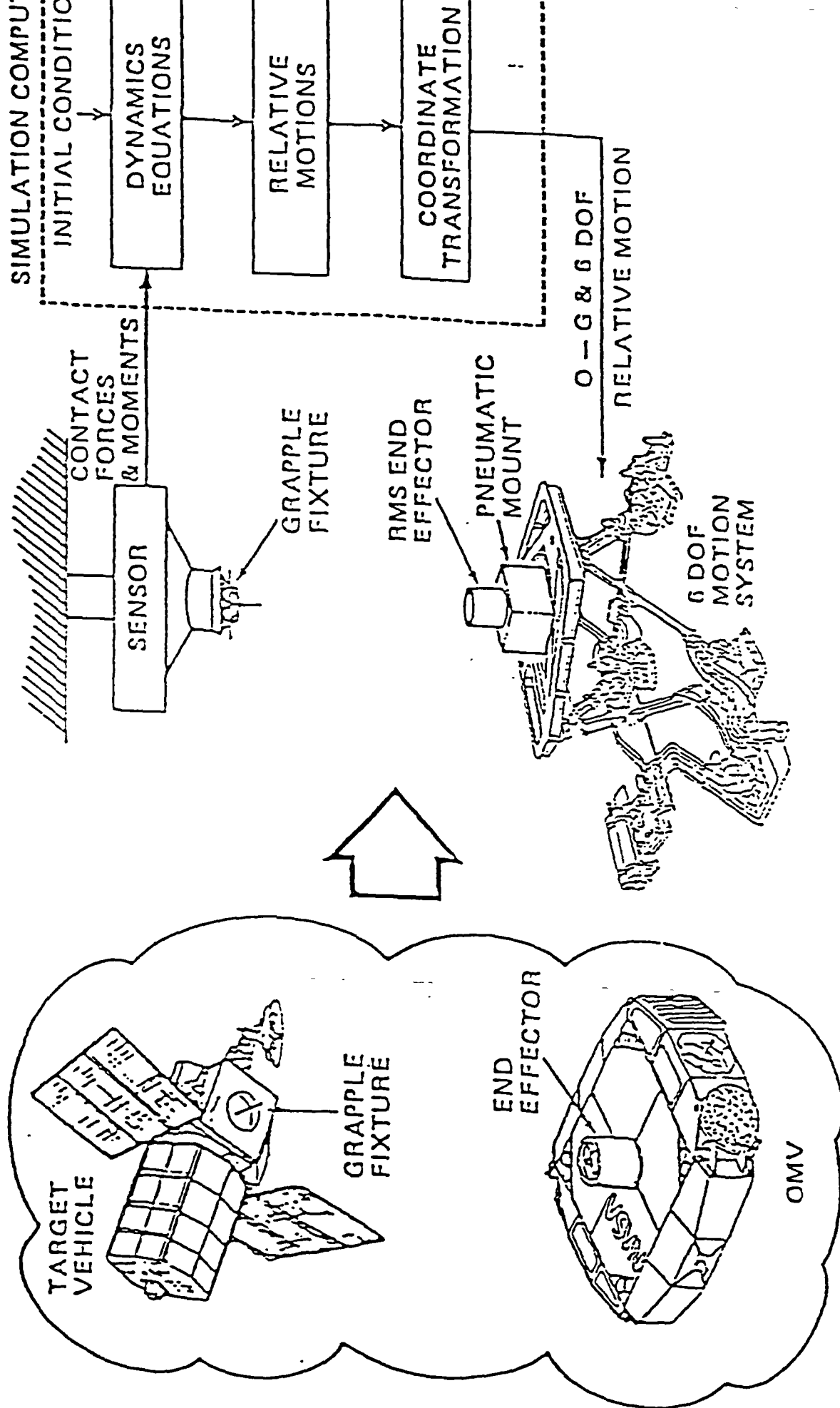
## 1.0 INTRODUCTION

The Space Station Mechanism Test Bed is a six degree of freedom (DOF) motion simulation facility used to evaluate docking and berthing hardware mechanisms. The major components of the Mechanism Test Bed (MTB) are shown in Figure 1.0-1. The chase vehicle docking mechanism is mounted on the hydraulically driven, computer controlled, six DOF motion system. The target vehicle docking mechanism is mounted in conjunction with a force and moment sensor to the facility ceiling. Mechanism contact forces and moments are measured and supplied to the host computer (i.e., currently, an Alliant computer) for use in the dynamics model.

Under contract NAS8-36570, Control Dynamics (CDy) developed a generalized rigid body math model to replace the "old" model which was based on several restrictive assumptions (e.g., one body was assumed to have much greater mass than the second and therefore was unaffected by contact forces and moments). The "new" model allowed the computation of vehicle relative motion in six DOF due to forces and moments from mechanism contact, attitude control systems, and gravity. No vehicle size limitations were imposed in the model. The equations of motions were based on Hill's equations for translational motion with respect to a nominal circular earth orbit and Newton-Euler equations for rotational motion. Over the past several years, CDy has worked with NASA in refining this rigid body model and the supporting software.

This report documents the development of a generalized flexible body math model to further enhance the MTB simulation capabilities. Although the original contract plan was to modify the current rigid body model, early investigations showed that a "fresh start" approach to the flex body model would yield a more efficient simulation. The development and major components of the flex body math model parallel those of the rigid body model.





CONTACT DYNAMICS USING 6 DOF MOTION SYSTEM

Figure 1.0-1

Section 2.0 of this report summarizes the rather mathematically intense derivation of the equations of motion for a single generic flexible body. The derivation is based on Lagrange's quasi-coordinate equations. Section 3.0 describes the method used to transform contact forces and moments from the sensor location to each body docking port. Section 4.0 discusses the computation of the relative body motion data: (1) relative orientation, (2) relative position, (3) relative translational velocity, and (4) relative angular velocity. This data is required in the interface between the dynamic math model and the main simulation. Section 5.0 describes the major components of the math model FORTRAN simulation including the required input data and a pre-processing algorithm for flexible body data. The model was coded with user selectable options regarding the method of integration and the complexity of the equations of motion. These options are discussed in Section 5.0 along with the governing input data. Section 6.0 discusses the many tests used to verify the flex body math model in progressive steps. Time domain comparisons to the multi-flex body code called TREETOPS are also presented. Section 7.0 contains a brief summary with concluding remarks. Appendices A and B contain a listing of the flexible body math model code and definitions for the math model global simulation variables, respectively. Finally, Appendix C contains a listing of the flexible body data pre-processing algorithm.



**AIAA 92 - 1688**

**Automated Rendezvous and Capture  
at NASA / MSFC**

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**AIAA Space Programs  
and Technologies Conference**  
March 24-27, 1992 / Huntsville, AL

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## Introduction

Ground based testing of prototype and flight hardware is a necessary step in the design process of aerospace systems. Innovative real time hardware in the loop simulation facilities can fill this need in a cost efficient manner. This need is especially evident in the evaluation and qualification of automatic and man in the loop rendezvous and capture systems. Flight demonstrations of this technology will require two free flying vehicles and launch systems. Although a flight demonstration must ultimately be performed to prove a system, the cost dictates that only the most promising candidates be tested in this manner. Ground based testing should be used to select the best systems available for flight demonstration. Analytical techniques and simulations, as well as ground based testing, should be used throughout the entire design process to expose problems early in the design process to expose problems early in the design stage, enhance performance, and reduce redesign cost.

At the Marshall Space Flight Center (MSFC), there are two complimentary hardware in the loop simulation facilities used to test rendezvous and capture systems.

The Flight Robotics Laboratory uses an eight degree of freedom overhead manipulator to simulate two rigid vehicles in a circular orbit. Range/rate sensors are attached to mock ups in the facility and interface to the real time computer system. Automatic rendezvous algorithms are integrated into the simulation software and generate control system commands for the chase vehicle. The vehicle equations of motion are driven by control systems and gravitational effects and solved numerically. The manipulator follows the simulated relative motion between the two vehicles. The facility is best suited for examining the performance of the range/rate sensor and rendezvous algorithm up to the point of contact.

The Space Station/Space Operations Mechanism Test Bed (SIX DOF Facility) uses a six degree of freedom hydraulic table to simulate the docking of two flexible vehicles or the berthing process between two vehicles using the Orbiter RMS manipulator. The two halves of the capture

mechanism are installed in the facility, one to the table and the other to a force/moment sensor in the ceiling. The sensor measures the resultant contact forces and moments and transfers this data to the real time computer system. Contact forces and moments, gravitational effects, and vehicle control systems drive the equations of motion governing the docking or berthing process. The table follows the resultant relative motion between the two vehicles. This facility is designed to evaluate the capture mechanism itself by simulating the contact dynamics interaction between the mating vehicles.

# **RMS SOFTWARE OVERVIEW AND OPERATIONS MANUAL**

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February 26, 1993

Submitted to:  
Marshall Space Flight Center  
Division EB44  
Huntsville, AL

NASA Contract NAS8-38771

## 1.0 INTRODUCTION

Logicon Control Dynamics (LCD), under contract to the Marshall Space Flight Center (MSFC), developed a real-time Remote Manipulator System (RMS) simulation for use in Space Station Freedom assembly studies. The RMS simulation is an integral part of MSFC's 6-DOF motion simulator. The 6-DOF simulator's primary purpose is the study of space vehicle contact-dynamics during orbital docking and berthing. This RMS simulation was later modified by LCD in support of Boeing's 6-DOF Common Berthing Mechanism (CBM) hardware-in-the-loop (HITL) development tests.

The purpose of this document is to present a detailed software description and the operational procedures for the simulation. Chapter one presents the history associated with the model's development and defines the purposes and organization of this document. Chapter two presents a simulation overview including a description of the simulation's modes-of-operation. Chapter three discusses the theory behind the dynamics modeling, the RMS control system implementation, and defines the necessary simulation coordinate frames. Chapter four provides detailed descriptions of the operational procedures for each mode-of-operation. Chapter five contains the summary and some recommendations. Appendices A, B and C contain additional information supporting the above chapters.

This RMS model was patterned after Johnson Space Flight Center's SES RMS model. The SES simulation was developed primarily for crew training purposes. The SES RMS simulation software was shipped to MSFC in February of 1989. Upon initial evaluation, it was apparent that SES software was not formulated for its intended use in contact-dynamics studies at MSFC. Additionally, the software was not portable to the 6-DOF's Alliant computer. It was written in machine dependent Gould Fortran and partially in assembler.

LCD wrote the MSFC RMS software using RMS control algorithms based on RMS documentation (Ref. 1 and 2). Also, a complete rewrite of the RMS dynamics routines was necessary to allow CBM loads into the EOMs. Originally, the model was developed as a non-real-time serially executing simulation written entirely in standard Fortran-77.

However, conversion to a real-time simulation was necessary for contact-dynamics studies at the 6-DOF facility.

To achieve a real-time status, the simulation was broken into three separate parallel executables with timing-control embedded in the main process. The parallel version uses shared memory regions to pass variable values between processes. The software associated with the creation and attachment to these shared regions is the only machine dependent software (Alliant computer systems) in the RMS software.

Both versions of the simulation (serial and parallel) still exist and are maintained. In 1992-93, the parallel version was successfully used in Boeing's D08B Development Tests and in a first-cut software-only (with SGI graphics) MITL visual queues (targets) evaluation. The serial version has been incorporated into a detailed analytical contact dynamics simulations (ACDS). The ACDS simulation (see Ref. 3) simulates berthing operations using a contact force model of Boeing's CBM.



**Characterization Test Procedure  
and Results  
for the  
DOTS Joint Servo System**

Michael J. Dendy  
June, 1993

**LOGICON**

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## Introduction

This document describes the setup and procedure for the experimental characterization of the DOTS joint servo system. The entire DOTS system, including the servos, was first characterized in 1988; the results are documented in the *Flight Robotics Laboratory Final Report, Volume IV: Facility Hardware test Results*. Since that time, extensive use and changes in the servo system and manipulator hardware have made it necessary to repeat the characterization of the servo portion (particularly the inner or rate loop) of the DOTS system. The new results are presented and compared to the results of 1988.

Figure 1 is a block diagram of the overall system for the actuation of any given DOTS joint. For the measurements described in this section, the test signal is injected at the positive input to summing junction B while the response is measured at the negative input to B.

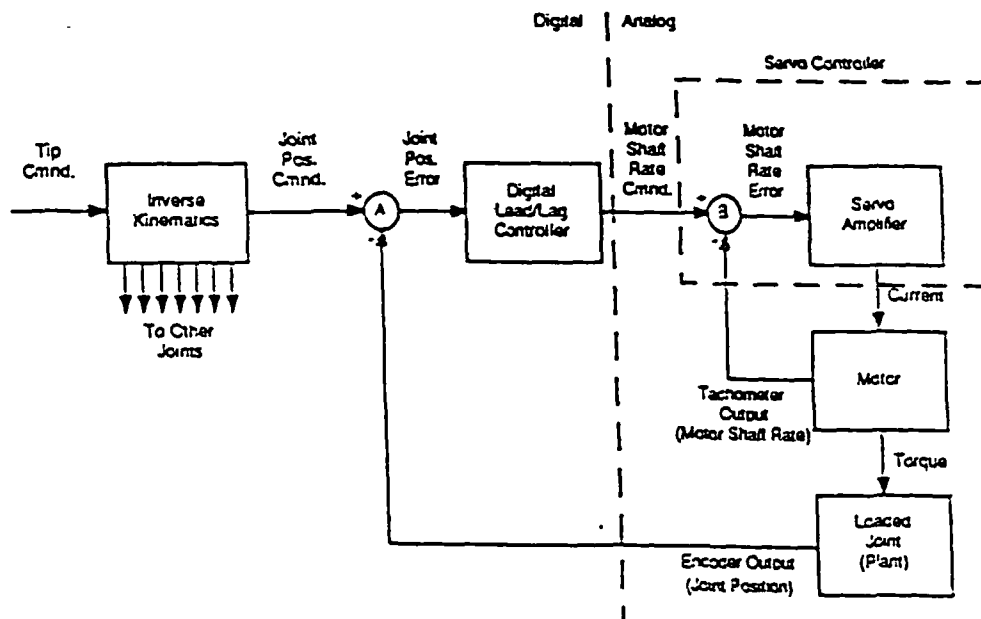


Figure 1 - DOTS Joint Control System

# **A Testbed for Research on Manipulator-Coupled Active Spacecraft**

**Raymond C. Montgomery, Patrick A. Tobbe,  
John M. Weathers, Dave Ghosh, and James L. Garrison**

**Spacecraft Controls Branch  
NASA Langley Research Center  
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**AIAA Guidance, Navigation, and Control Conference**

**August 9-11, 1993  
Monterey, California**

## Introduction

The capture and berthing of a controlled spacecraft using a robotic manipulator is an important technology for future space missions and is presently being considered as a backup option for direct docking of the Space Shuttle to the Space Station during assembly missions. The berthing operation considered assumes that, first, the Space Shuttle Remote Manipulator System (RMS) grapples Space Station. Next, the RMS joint brakes are applied and the combined Station, RMS, and Shuttle stack are maneuvered to a torque-equilibrium attitude using the Station RCS jets. Finally, the RMS brakes are released and retraction takes place. The unusual feature of this operation is that control of the attitude is accomplished by the Space Station Control Moment Gyro (CMG) system during retraction of the RMS. Control of the RMS is located on the Space Shuttle and the attitude control deadbands in the Space Shuttle Digital Autopilot are enlarged to prevent firing of its RCS jets during retraction. Vibrations of the stack are of concern during this operation and it is desirable to have the RMS controllers and the CMG system on the Station cooperate in an attempt to suppress them.

Previous research in vibration control of manipulators with payloads has been directed at using joint motors only [1], [2], [3], [4], and [5]. Manipulator control wherein the payload has an independent attitude control system has not been accomplished in space. Research is needed to define possible cooperative control roles for the manipulator and the independent attitude control systems. One role would be for the spacecraft attitude control system to aid in suppressing relative vibrations. To the authors' knowledge the first proposal to use active inertial devices to control the vibrations of robot arms was by Timmerman and Dickerson [6]. In the paper the concept was put forth and explained using a simple spring-mass system. Reference [7] provides a theoretical development and simulation study of a two-link manipulator wherein a torque-wheel device was evaluated for improving the telerobotic performance of a robot arm. Therein, it was shown by simulation that the use of a torque-wheel could substantially reduce the overshoot occurring as a result of a sudden stop command from the operator. Thus, the device would be useful in suppressing vibrations at the payload end and generally in improving the human handling

qualities of a telerobotic arm. The size of the arm used was approximately that of the RMS and the torque-wheel was sized to produce 60 ft-lbs at .5 Hz. In that work the effects of flexibility were lumped in the gear box of the joint motors. The use of both torque and force devices has been studied in [8]. Therein, a torque-wheel and a reaction-mass actuator were studied on the payload end of a single link manipulator. Linear, quadratic, regulator theory was used to design the controller for that work. Again the simulations were constrained to lumped flexibility and the inertial devices were found to be useful in suppressing vibrations. The reaction-mass actuator, however, seemed to have an advantage over the torque-wheel both in weight and effectiveness. Later simulation work was reported, [9] and [10], wherein a torque-wheel and a reaction mass actuator were used in a distributed simulation of the flexibility of a single-link arm. Reference [9] proposed an active inertial device that would interface between the payload and the current end effector of the RMS to provide isolation of the payload from vibrations of the RMS.

The dynamics and control of spacecraft configurations that are manipulator-coupled with each spacecraft having independent attitude control systems are not well understood and NASA is actively involved in both analytic research on this three-dimensional control problem for manipulator-coupled active spacecraft and experimental research using a two-dimensional ground-based facility at the Marshall Space Flight Center (MSFC). This report first describes the MSFC testbed. This is followed by a description of simulators that have been developed to facilitate testbed design, control theory development, and test planning. Results from the initial test program conducted in December of 1992 are then presented along with a description of the output matching system identification used to tune the simulators.

**Results of the DOTS Joint  
Position Response  
Tests**

August, 1993

Michael J. Dendy  
Patrick A. Tobbe  
Charles B. Naumann

**LOGICON**

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**Control Dynamics Company**

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## DOTS Encoder Alignment Procedure

Michael J. Dendy  
Patrick A. Tobbe

September, 1993

### **LOGICON**

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## **Introduction**

In February of 1993, tests were conducted to characterize the performance of the Dynamic Overhead Target Simulator (DOTS) of the Flight Robotics Laboratory. The tests were conducted by introducing a series of position profiles to the system in both joint space and tip space. This memorandum describes the test configuration and presents the test results. Sensed or sensor-derived responses are compared to commanded inputs and recommendations for changes or improvements to the system are made based on the results.



## Introduction

The sensors that provide joint position information for the Digital Overhead Target Simulator (DOTS) arm are absolute digital encoders. The encoder resolutions are fixed through mechanical means and they have been calibrated to ensure accuracy. However, the encoder values for given joint positions may vary after a period of time due to slippage or alteration of the encoder/joint coupling mechanisms. Therefore, the "home" position should be checked and recalibrated periodically. The purpose of this memorandum is to describe the procedures necessary to ensure proper operation of the DOTS encoders. It includes descriptions of the arm and flat floor geometries, the algorithm for computing joint positions for encoder data, and a suggested encoder alignment procedure.

**Note:** The DOTS encoders referred to in *Results of the DOTS Joint Position Response Test* were replaced in 9/93 with higher resolution encoders. This document pertains to the new encoders and includes the new resolutions.

# A Study of Active Isolation Systems for the RMS

Submitted to:

National Aeronautics and Space Administration  
George C. Marshall Space Flight Center  
Marshall Space Flight Center, AL 35812

Under Contract:

NAS8-38771

July 15, 1994

**LOGICON**

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## **Active Isolator Study**

### **Introduction**

The capture and berthing of a controlled spacecraft using a robotic manipulator is an important technology for future space missions and is presently planned for early Space Station assembly missions. The capture and berthing operations require precision telerobotic maneuvering of large payloads by the astronauts using the Remote Manipulator System (RMS) of the Space Shuttle. Since the RMS was not designed with this in mind, augmentation of the system may be needed. The problem of concern is controlling the motions of the payload during start-up and stopping for large payloads. During these operations, the direction of motion of the payload is difficult to predict because of start-up transients and the vibration environment of the system. An augmentation is desirable that will allow precision payload positioning and active control of the load transmitted to the payload. A requirement is that the augmentation should solve the problem with little or no impact on the existing RMS. The potential solution proposed herein involves an independent device called an End-Point Control Unit (EPCU) that interfaces between the payload and the end-effector of the RMS and actively controls loads transmitted to the payload using active compliance and/or inertial load relief. The EPCU concept applies to a broad range of devices that interface between the end of a manipulator and the payload and which provide vibration isolation through active compliance and/or inertial load relief using inertia devices such as control moment gyros, reaction wheels, or reaction mass actuators. The EPCU would be a tool, stored in the payload bay until needed, picked up by the RMS or other compatible telerobotic manipulator, and then used to grapple the payload. Astronaut inputs would be provided via a Power/Data Grapple Fixture (PGDF) which would return appropriate signals so that the astronaut can monitor safe operation of the unit.

UPDATE TO THE CHARACTERIZATION  
TEST PROCEDURE FOR THE DOTS  
JOINT SERVO SYSTEM

July 1994

Submitted To:

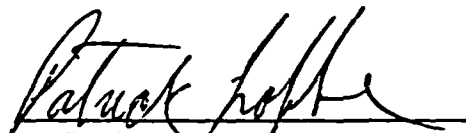
Marshall Space Flight Center  
Astrionics Laboratory  
Orbital Systems and Robotics Branch  
Huntsville, AL

Prepared By:



Marlin Williamson  
Member of Technical Staff

Program Manager Approval:



Dr. Patrick A. Tobbe  
Manager, Space Systems Branch

## 1.0 Introduction

Since the last DOTS joint servo system characterization test procedure document was published [1,2], the DOTS hardware has been significantly altered. The DOTS host computer has been replaced with a real-time Night Hawk machine and is now located on the service platform attached to the bridge. Extensive rewiring of the system was completed prior to testing. The CMR21 has been removed along with other hardware no longer required to transmit information between the DOTS hardware and the controlling computer. During the rewiring work, the tachometer cards were deleted and the scaled armature current signals were interfaced to the computer.

This document will again outline the procedure to properly set the Allen Bradley 1388 rate servo controllers for the DOTS robot. The visual inspection procedure of the servo controllers remains unchanged, but is again presented here for completeness. The square wave rate tests have been modified to take advantage of the high sample rate of the Night Hawk system. The square wave commands are generated by the computer and are used to drive a single servo at a time. The only other hardware needed to perform the tests is the HP Dynamic Signal Analyzer. The analyzer is used to collect data (tachometer and scaled armature current signals). The tests to determine the joint design plant transfer function (from servo rate command to joint position) will be documented in a separate report. However, the tachometer signals will be compared against the differentiated encoder data (collected by the computer) in order to initially characterize the transfer function from motor space to joint space.

The maximum allowable rates for each joint have been decreased to command a slower speed (the LSB of the command results in a slower motor speed) and reduce potential wear due to high speeds. The rates had been set to obtain the rated speed of the motor when the maximum ten volt command had been sent to the servos. The procedure to scale the speed will be presented.

Section 2 contains the procedure for visual inspection of the rate servos and the test set up and procedure for the square wave tests. The method of obtaining the desired speed for a given command is also discussed. The results from these tests are contained in Section 3.0 with concluding remarks found in Section 4.0.

# **Testing of an End-Point Control Unit Designed to Enable Precision Control of Manipulator-Coupled Spacecraft**

**Raymond C. Montgomery and Dave Ghosh**

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NASA Langley Research Center  
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**Patrick A. Tobbe and John M. Weathers**

**Logicon Control Dynamics, Inc.  
Huntsville, Alabama 35802**

**Davoud Manouchehri and Thomas S. Lindsay**

**Rockwell Space Systems Division  
Downey, California 90241**

**AIAA Space Programs and  
Technologies Conference and Exhibit**

**September 27-29, 1994**

**Huntsville, Alabama**

## Introduction

The capture and berthing of a controlled spacecraft using a robotic manipulator is an important technology for future space missions and is presently planned for early Space Station assembly missions. The capture and berthing operation requires precision telerobotic maneuvering of large payloads by the astronauts using the Remote Manipulator System (RMS) of the Space Shuttle. Since the RMS was not designed with this level of precision in mind, augmentation of the system may be needed. The problem of concern is controlling the motions of large payloads during start-up and stopping. During these operations, the directions of motion of the payload is difficult to predict because of start-up transients and the vibration environment of the system. Augmentation that will allow precision payload positioning and active monitoring of loads transmitted to the payload is desirable. A requirement is that the augmentation should solve the problem with little or no impact on the existing RMS. The potential solution proposed herein involves an independent device called an End-Point Control Unit (EPCU) that interfaces the payload and the end-effector of the RMS and actively controls loads transmitted to the payload using active compliance and/or inertial load relief.

The EPCU is positioned between the end of a manipulator and the payload and provides vibration isolation through active compliance and/or inertial load relief using inertia devices such as control moment gyros (CMGs), reaction wheels, or reaction mass actuators. The EPCU would be a tool, stored in the payload bay until needed, picked up by the RMS or other compatible telerobotic manipulator, and used to grapple the payload. Astronaut inputs would be provided via a Power/Data Grapple Fixture (PDGF) which would return appropriate signals so that the astronaut can monitor safe operation of the unit.

Previous research in vibration control of manipulator arms with large payloads has been directed at using joint motors only [1]. To the authors' knowledge, the first proposal to use active inertial devices to control the vibrations of robot arms was by Timmerman and Dickerson [2]. In that

paper, the concept was put forth and explained using a simple spring-mass system. Reference[3] provides a theoretical development and simulation study of a two-link manipulator arm wherein a torque-wheel device was evaluated for improving the performance of a robot arm. Therein, it was shown by simulation that the use of a torque-wheel could substantially reduce the overshoot occurring as a result of a sudden stop command from the operator. Thus, the device would be useful in suppressing vibrations at the payload end and generally in improving the operability of a manipulator arm.

An active inertial device that is positioned between the payload and the current end-effector of the RMS and provides motion and vibration isolation was proposed in [4]. Active compliance alone was also proposed as a potential solution to the problem in [5]. Therein, active compliance was investigated using a simulation of a hardware testbed available at the Marshall Space Flight Center [6]. The mechanism simulated used a direct drive motor mounted to the manipulator end of the device to drive a connecting rod attached to the payload end via a load cell. Thus, the load transmitted to the payload could be directly controlled via a high gain feedback loop from the load cell to the motor. This paper is, in fact, a continuation of that research and focuses on the initial tests conducted at the Marshall Space Flight Center. The paper presents a brief description of the EPCU concept and design, overviews the facility at MSFC [6] which has been used to test the device, describes a simulator for the facility with the EPCU installed, presents initial simulation results which show that the device has the potential of isolating the payload motions from vibrations of the arm, and presents results taken from the May 1994 test program at MSFC.



# **RMS MATH MODEL UPGRADES AND SIMULATION VALIDATION SUPPORT**

Prepared by:  
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September 20, 1994

Submitted to:  
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Simulation Systems Branch / EB63  
Huntsville, AL

NASA Contract NAS8-38771

## 1.0 INTRODUCTION

Control Dynamics (CDy), a division of bd Systems, under contract to the Marshall Space Flight Center (MSFC), developed a real-time Remote Manipulator System (RMS) simulation for use in Space Station Freedom assembly studies. The RMS simulation is an integral part of MSFC's 6-DOF motion simulator. The 6-DOF simulator's primary purpose is the study of space vehicle contact-dynamics during orbital docking and berthing. This RMS simulation was later modified by CDy in support of Common Berthing Mechanism (CBM) hardware-in-the-loop (HITL) development tests.

The purpose of this document is to present enhancements made to the simulation in support of the formal RMS math model validation process. The most significant upgrade to the model is the replacement of the free-free substructure modes which describe the flexibility of the RMS booms with a user defined number of constraint / fixed interface modes. Other changes to the model include sensor quantization effects, servo electronics state space representation, and orbiter thruster firing inputs.

In support of the validation process, software was written to compute internal RMS member loads at the strain gage locations near the shoulder pitch and wrist pitch joints. The RMS software was modified to update the termination conditions for the single joint and direct drive modes of operation. The simulation output routines were also changed to compute data in the proper format for validation. Parameter studies were performed to examine the effects of the number of substructure and system modes on the accuracy of the system response. Studies were carried out to assess the friction parameters and numerical integration step size.

Section 2.0 of this report documents the upgrades to the math model. The strain gage force/moment algorithm and software is described in Section 3.0. Section 4.0 presents the results of the parameter studies. Conclusions and recommendations are made in Section 5.0.

## Technical Memorandum

Author: Marlin J. Williamson

Date: October 29, 1994

Subject: Feasibility Study of a Pneumatic Actuator for TVC Control

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The availability of gaseous hydrogen on liquid propellant launch vehicles warrants the investigation of the capabilities of a pneumatic actuator for replacement of a hydraulic actuator. The savings would be in the weight loss of the system used to provide the pressurized hydraulic oil. It may be possible to simplify the TVC system with a pneumatic actuator.

This paper provides a first cut investigation into the capabilities of a pneumatic actuator. The performance criteria used in this study were: 1) follow a ramp command as closely as possible and 2) minimize the response due to force disturbances on the load.

The compressibility of gaseous hydrogen is much greater than that of hydraulic oil. Therefore, the resulting pneumatic system is much softer than a comparable hydraulic system. The resonant frequency is expected to be lower in the pneumatic system. These characteristics make the control design problem more difficult in the pneumatic design if the performance is to match that of a comparable hydraulic system.

In order to stiffen the pneumatic system, pressure feedback is investigated. Rate feedback (piston rate) is also investigated as a possible way to produce a stiffer pneumatic system. A non-linear model of a pneumatic actuator system is developed for use in performance evaluations. The linearization of this model is provided in order to perform frequency domain analysis and control designs. Results of both models are presented along with concluding remarks

# **SIMULATION AND TESTING OF A ROBOTIC MANIPULATOR TESTBED**

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**PATRICK A. TOBBE AND JOHN M. WEATHERS**  
bd Systems, Control Dynamics  
Huntsville, AL

**THOMAS S. LINDSAY**  
Rockwell International  
Downey, CA

**TENTH VPI&SU SYMPOSIUM ON  
STRUCTURAL DYNAMICS AND CONTROL**

**BLACKSBURG, VIRGINIA  
MAY 8-10, 1995**

## Introduction

The handling of a large controlled spacecraft using a robotic manipulator is an important technology for future space missions and is presently planned for early Space Station assembly missions. The operations planned require precision telerobotic maneuvering of large payloads by the astronauts using the Remote Manipulator System (RMS) of the Space Shuttle. The focus of this research is aimed at controlling the motions of large payloads (on the order of the size of the Space Shuttle itself) during the start-up and stopping transients that result from the flexibility of the manipulator-coupled system.

During start-up and stopping, the direction of motion of a large payload is difficult to predict because of start-up transients and subsequent vibration in the system. One fix for this problem is to conduct the operation slowly, in steps, and minimize the excitation. If objectional vibration does occur, then, extra time is required for them to settle out. This solution, although immediately implementable with no new technology, carries with it the penalty of extending the time required for operations. As long as the time required to accomplish the maneuvers is not an issue, this solution is adequate, barring frustration of the human operator. However, the cost of orbit time is high and, if multiple launches are required, an entire launch may possibly be avoided if mission time lines can be accelerated and the utility of the current RMS can be expanded to include additional precision operations. Hence, NASA continues to develop telerobotic technology that addresses these problems.

Both simulation and hardware testbeds have been developed for advancing telerobotic technology. In simulation, batch and man-in-the-loop simulators with realistic display and control interfaces are used. Concerning hardware testbeds, ground testing of hardware is necessarily compromised since providing the zero-gravity of space is not possible. To overcome this difficulty, techniques have been developed using hybrid simulators wherein the interface loads to specific hardware components are computer driven to simulate the external space environment of

the component [1]. Additionally, NASA facilities have been developed for planar motion that allow testing hardware in essentially a frictionless, free-free environment. One such facility is located at the G.C. Marshall Space Flight Center (MSFC). Using the MSFC facility, a testbed for developing hardware components and control system techniques for manipulator technology has been developed [2]. At this time the testbed consists of an anthropomorphic manipulator with the shoulder attached to a wall of the facility and the wrist attached to a large payload. The payload and the elbow joint of the manipulator are supported using air bearings. The next phase of the testbed evolution calls for construction of another payload to replace the wall attachment so that free-free operation can be evaluated. This paper is a progress report which discusses overall problems of the telerobotic control of space robots, overviews the development of the testbed, and presents results of hardware component testing accomplished to this time and results of simulation studies on the planned free-free testbed.

**Technical Report**

**SIMULATION OUTPUT SUMMARY**

**STATISTICAL MODEL OF A GLOBAL POSITIONING  
SYSTEM RECEIVER AND CONSTELLATION**

15 May 1995

**Submitted To:**

Procurement Office  
Attn: Jim Lomas, EL58  
George C. Marshall Space Flight Center  
Marshall Space Flight Center, AL 35812

**Prepared by**

Control Dynamics, A Division of bd Systems, Inc.  
600 Boulevard South, Suite 304  
Huntsville, AL 35802

## **1.0 INTRODUCTION**

### **1.2 Purpose**

This document summarizes the outputs from the Global Positioning System Digital Statistical Receiver and Constellation Model (GPS-RCM) developed by Control Dynamics (CDy), a division of bd Systems, for the Automated Rendezvous and Capture (AR&C) Program. The document discusses the simulation output as compared to the requirements set forth in the statement of work.

### **1.2 Organization**

Section 2.0 of this document presents typical navigational accuracy results produced by the GPS-RCM simulation. The absolute navigation requirements of the GPS simulation are discussed in conjunction with the typical simulation results.

Section 3.0 contains a description and discussion of the emulated receiver outputs. Section 3 present data from both the simulation and a data tape provided by Mayflower.

Section 4.0 contains a brief summary with concluding remarks.



Technical Report

**SIMULATION USER'S MANUAL**

**STATISTICAL MODEL OF A GLOBAL POSITIONING  
SYSTEM RECEIVER AND CONSTELLATION**

15 May 1995

Submitted To:

Procurement Office  
Attn: Jim Lomas, EL58  
George C. Marshall Space Flight Center  
Marshall Space Flight Center, AL 35812

Prepared by

Control Dynamics, A Division of bd Systems, Inc.  
600 Boulevard South, Suite 304  
Huntsville, AL 35802

## **Introduction**

### ***1.2 Purpose***

This document describes the Global Positioning System (GPS) Digital Statistical Receiver and Constellation Model developed by Control Dynamics (CDy), a division of bd Systems, for the Automated Rendezvous and Capture (AR&C) Program. The document serves as both a user's guide and a software design reference document.

### ***1.2 Organization***

Section 2.0 of this document gives a general description of how the AR&C-GPS simulation interfaces with the Flight Robotics Laboratory (FRL) and the major components which comprise the simulation. General form equations are given for the pertinent component models along with a description of the terms which appear in the equations.

Section 3.0 contains detailed information describing each major subroutine in the simulation and the input data which can be modified by the user to reconfigure the simulation. This section is most useful for the end user of the simulation.

Section 4.0 presents some typical results from the simulation. The results presented in this section are based on GPS users (chaser and target) located near the surface of the Earth and rotating with Earth. The results were generated in a "self-contained" version of the software (i.e., no laboratory interfaces were involved).

Section 5.0 contains a brief summary with concluding remarks. Appendix A contains example GPS almanac data taken from the GPS bulletin board at Colorado Springs, Colorado. Appendix B contains an example listing of the simulation initialization/configuration input file ARC\_GPS.DAT. Appendix C contains a listing of the simulation source code.

**Solar Simulator Interface**  
**Version 0.1**

**Prepared by**  
**Charles Naumann**  
**Control Dynamics, a division of bd systems**

**for**

**GEORGE C. MARSHALL SPACE FLIGHT CENTER**  
**MARSHALL SPACE FLIGHT CENTER, ALABAMA 35812**

**Under:**

**Contract No. NAS8-38771**

**July 11, 1995**

## **Introduction**

The solar simulator is a bank of six high intensity flood light capable of illuminating a target in the work volume of the DOTS with an intensity equal to that of the sun. The solar simulator can translate the length of the DOTS and can be rotated about a vertical axis.

The solar simulator may be operated autonomously, or synchronized to a simulation hosted on the DOTS computer. This document explains the interface and the protocol for the exchange of data between the solar simulator and the DOTS computer.

Contract NO. NAS8-30771

RESULTS OF THE DOTS JOINT  
POSITION RESPONSE TESTS

30 October 1995

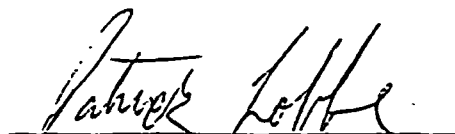
Submitted To:

Marshall Space Flight Center  
Astrionics Laboratory  
Orbital Systems and Robotics Branch  
Huntsville, AL

Prepared By:

  
Marlin Williamson  
Member of Technical Staff

Program Manager Approval:

  
Dr. Patrick A. Tobbe  
Manager, Space Systems Branch

## 1. Introduction

In February of 1993, tests were conducted to characterize the performance of the Dynamic Overhead Target Simulator (DOTS) of the Flight Robotics Laboratory. The results are documented in **Results of the DOTS Joint Position Response Tests [1]**. Similar tests were conducted in the spring of 1995 after an upgrade to the digital joint position controllers and higher resolution encoders were installed. All of the joint controllers were tuned for improved performance. The upgrade included an added rate loop about the waist joint. A tachometer was installed to measure the rate of change of position of the waist at the output of the gear box. The flexibility of this joint has been of concern. The added instrumentation allowed for the flexibility information to be incorporated into the new control law. These tests were also repeated in the fall of 1995.

This document records the DOTS position responses in joint space and tip space. The tests were conducted by introducing a series of commanded position profiles for single joints or coordinated tip motion (several joints commanded). This memorandum describes the test configuration and presents the test results. Sensored or sensor-derived responses are compared to commanded inputs and recommendations for changes or improvements to the system are made based on the results.

The goal of the DOTS tests was to measure the response of the system to computer-commanded position profiles. Tests were used also to tune the new controllers. The test results presented were conducted with the final controllers present. The tests were done in two modes: joint-space mode; in which one joint can be commanded directly, and tip-space mode; in which the position of the tip is commanded and the necessary joint commands are derived in the inverse kinematics routine. For each test conducted in joint-space, an individual joint was commanded with a position step command while the other joints are disabled. Nominal rate limits were imposed for the position step tests in joints space. Much lower rate limits were imposed during the ramp tests in joint space.

For the tip-space tests, individual axes as well as multiple axes of both translation and rotation were commanded with input profiles in the range of tip motion expected for the AR&C program.

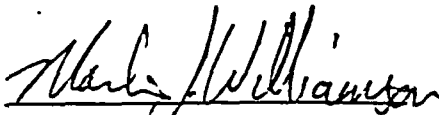
**DYNAMIC OVERHEAD TARGET  
SIMULATOR USERS' GUIDE**

30 October 1995

Submitted To:

Marshall Space Flight Center  
Astrionics Laboratory  
Orbital Systems and Robotics Branch  
Huntsville, AL

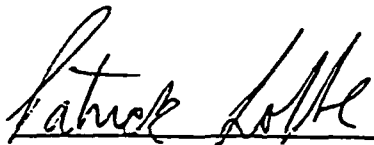
Prepared By:



Marlin Williamson  
Member of Technical Staff

\_\_\_\_\_  
Charles Naumann  
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Program Manager Approval:



Dr. Patrick A. Tobbe  
Manager, Space Systems Branch

## 1.0 Introduction

The Flight Robotics Laboratory of the Marshall Space Flight Center provides sophisticated real time simulation capability in the study of human/system interactions of remote systems. The facility consists of a 5800 square foot precision air bearing floor, teleoperated mobility base, overhead electric manipulator, solar simulator, remote operator's work station, real time computer system, and various mock ups. This facility has been used to study the performance of automatic or man-in-the-loop rendezvous systems in a real time environment. These studies investigate the performance of the automatic rendezvous algorithms, range/rate sensors, and human factor concerns such as light and camera placement, control system sensitivity, and transmission time delays for man-in-the-loop operations.

The overhead manipulator or Dynamic Overhead Target Simulator (DOTS) is used for six degree of freedom motion of the mockups, typically in hardware-in-the-loop simulations. The purpose of this document is to present operating procedures for DOTS. This document will describe the facility geometry and coordinate frames, joint encoder calibration procedures, operating terminal display, DOTS modes of operation, DOTS control commands, and various safety concerns.



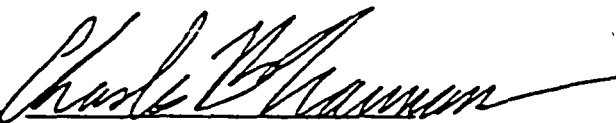
# DOTS SOFTWARE OVERVIEW

27 October 1995

Submitted To:

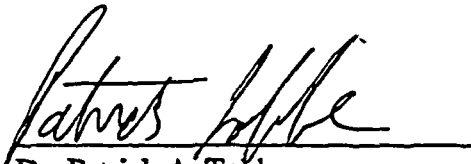
Marshall Space Flight Center  
Astrionics Laboratory  
Orbital Systems and Robotics Branch  
Huntsville, AL

Prepared By:



Charles Naumann  
Member of Technical Staff

Program Manager Approval:



Dr. Patrick A. Tobbe  
Manager, Space Systems Branch

## Introduction

This document is intended as a technical software reference for users who need to understand the internal workings of the DOTS code, especially for those users who intend to modify the code. This document is not intended as a user's guide for the operation of the DOTS facility or the engineering details of the simulations.

This document is to be used with past documentation (Specifically, *The Flight Robotics Laboratory Final Report*, March 1990, Volume I, *Real Time User's Manual*). A great many of the modules in use in the present version of the code are thoroughly discussed in these past reports. This document covers the changes made to the DOTS code as it was transferred from the VAX system to the Night Hawk computers. It includes a brief review of the evolution of the DOTS software, a description of the current software configuration, and shared memory regions.

NASA MSFC HARDWARE IN THE LOOP  
SIMULATIONS OF AUTOMATIC RENDEZVOUS  
AND CAPTURE SYSTEMS

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**LOGICON**

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**Control Dynamics Company**

## INTRODUCTION

This presentation will describe two complimentary hardware in the loop simulation facilities for automatic rendezvous and capture systems at the Marshall Space Flight Center. The Flight Robotics Laboratory uses an eight degree of freedom overhead manipulator with a work volume of 160 by 40 by 23 feet to evaluate automatic rendezvous algorithms and range/rate sensing systems. The Space Station / Space Operations Mechanism Test Bed uses a six degree of freedom hydraulic table to perform docking and berthing contact dynamics simulations.

**RMS PARALLELIZATION AT THE  
FLIGHT ROBOTICS LABORATORY  
ON THE SILICON GRAPHICS COMPUTER**

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Huntsville, Alabama 35802

Submitted to  
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## **RMS Parallelization at the Flight Robotics Laboratory on the Silicon Graphics Computer.**

### **Introduction**

A parallelized version of the RMS code is presently installed on the Alliant computer at NASA MSFC's 6 DOF facility. This software runs on a set of 8 processors with the most computationally intensive segment (2ms loop) distributed over 6 processors. At NASA MSFC's Flight Robotics Laboratory, A Silicon Graphics Computer 340 series computer was utilized to host a similar implementation of the RMS code. This machine has 4 processors of which 3 were utilized to run the three main segments of the code. The fourth processor was dedicated to system overheads such as communications to hardware (using Telnet protocol).

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| 16. Abstract<br><br>This report summarizes the work performed under contract NAS8-38771 in support of the Marshall Space Flight Center Six Degree of Freedom Motion Facility and Flight Robotics Laboratory. Major topics include a summary of reports written documenting the development of the two flexible body and Remote Manipulator System simulations, Dynamic Overhead Target Simulator control system and operating software, Global Positioning System simulation, and Lighting Imaging System technician support. |  |   |           |
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